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22%-Dynamically-Scaled Drop Model**

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## RESEARCH ON THE F/A-18E/F USING A 22%-DYNAMICALLY-SCALED DROP MODEL

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### ABSTRACT

Research on the F/A-18E/F configuration was conducted using a 22%-dynamically-scaled drop model to study flight dynamics in the subsonic regime. Several topics were investigated including longitudinal response, departure/spin resistance, developed spins and recoveries, and the falling leaf mode. Comparisons to full-scale flight test results were made and show the drop model strongly correlates to the airplane even under very dynamic conditions. The capability to use the drop model to expand on the information gained from full-scale flight testing is also discussed. Finally, a preliminary analysis of an unusual inclined spinning motion, dubbed the "cartwheel", is presented here for the first time.

### INTRODUCTION

Flight dynamic issues can significantly impact the safety and effectiveness of high-performance vehicles such as the Navy's latest strike aircraft, the F/A-18E/F Super Hornet shown in figure 1. Dynamic aspects often dominate the aerodynamics and can strongly influence the flight mechanics, particularly during the large-amplitude, high-rate maneuvering that is required of this class of aircraft. The typical challenge to the designer is to maximize maneuvering performance while maintaining good levels of departure resistance throughout the intended operational envelope and beyond (for margin).

A time-honored approach to achieve this balance between stability and maneuverability is to gain a comprehensive understanding of the aircraft flight dynamic properties by subjecting the configuration to a battery of tests.



Figure 1.- The F/A-18E/F Super Hornet

In the subsonic flight regime these tests (see figure 2) typically include captive and free-flying wind-tunnel tests (static force and moment, forced-oscillation, free-flight, free-spin, and rotary-balance, among others), outdoor drop model tests, numerical based analyses (e.g., piloted simulation studies), and culminate with full-scale flight testing. All of these tests were performed during the F/A-18E/F development; however, this paper concentrates on the drop model effort.

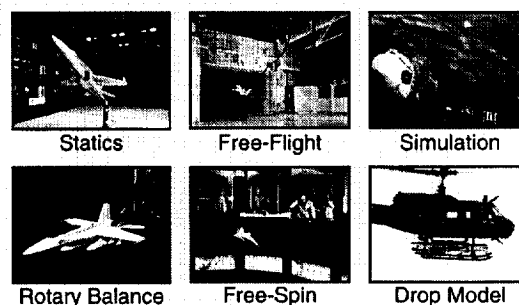


Figure 2.- Ground-based test methods.

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Drop model and aircraft flight test results covering a range of flight conditions and configuration arrangements are presented to illustrate some of the fundamental subsonic flight dynamic characteristics of the F/A-18E/F. In so doing, a sampling of the drop-model test technique capabilities is demonstrated.

Some of the drop model maneuvers were performed to compare to aircraft flight data; these comparisons are presented where available and show that the model method accurately represents the full-scale aircraft. Other drop model maneuvers were conducted to study areas outside of the scope of the aircraft flight test program that extended the depth of information on the F/A-18E/F design and flight dynamics in general.

### NOMENCLATURE

#### Symbols:

$A_{v\Omega}$	angle between velocity and rotation vectors, deg
$C_{l_p}$	roll damping coefficient
$C_L$	lift coefficient
$C_m$	pitching moment coefficient
$C_{m_q}$	pitch damping coefficient
$g$	acceleration due to gravity
$N$	model-to-airplane scale ratio
$p$	body-axis roll rate, deg/sec
$q$	body-axis pitch rate, deg/sec
$r$	body-axis yaw rate, deg/sec
$t$	time, sec
$V$	free-stream velocity
$\alpha$	angle of attack, deg
$\beta$	sideslip, deg
$\delta_{lat}$	normalized lateral stick, +=right
$\delta_{ped}$	normalized pedal, +=right
$\rho$	air density
$\psi$	heading angle, deg

#### Abbreviations:

CAS	control augmentation system
FCS	flight control system
LEF	leading-edge flap
LEX	leading-edge extension
SRYP	synchronous roll yaw parameter
TEF	trailing-edge flap

### DESCRIPTION OF TEST METHODS

The test methods used to generate the primary results presented within this report were the drop model technique and flight tests of the actual aircraft. As such, this section will focus on those two test methods even though the report contains limited results from other ground-based tests - specifically, captive wind-tunnel, spin tunnel, wind-tunnel free-flight, and simulation. Additional information about these test methods can be found in the references.<sup>1,2,3,4</sup> However, a general discussion of the non-captive scale-model test methods is given following a description of the aircraft and the full-scale flight test program.

#### Aircraft Description

The F/A-18E/F is a high performance, twin engine, supersonic fighter/attack aircraft. The airplane features twin canted vertical tails and moderately swept variable camber wings with leading edge extensions (LEX) extending from the wing root forward on each side of the fuselage. Two General Electric F414-GE-400 turbofan engines power the aircraft. The E-model is a single place aircraft; the F-model is a tandem two-place version of the E-model.

The F/A-18E/F flight control system is a digital, quadruplex, fly-by-wire, full authority control augmentation system (CAS). All control law computations are performed by four digital computers working in parallel. It includes a built-in redundancy management system that detects and isolates control system component failures. Due to control system component redundancy, multiple like failures are required before degradation in flying qualities or stability occurs. On the F/A-18E/F aircraft, no backup control modes are implemented where control of the actuators revert from CAS closed loop control to an alternate control function (e.g. no heavy mechanical backup). Instead, CAS operation always continues following failures to provide potentially degraded, but acceptable flying qualities.

Longitudinal control uses symmetric deflection of the stabilators, leading- and trailing-edge flaps, ailerons, LEX spoilers, and toe-in of the rudders. Lateral-directional control uses differential deflection of the stabilators, ailerons, leading- and trailing-edge flaps, and symmetric rudder deflection. In the takeoff and landing configuration, there is no differential deflection of the flaps.

## Full-Scale F/A-18E/F Flight Test Program

The full-scale flight test effort represented the largest and most aggressive high angle of attack program ever undertaken for the development of a production fighter.<sup>5</sup> Its scope included two distinctly different models (the single place E-model and two-place F-model), store loadings ranging from clean wing to a full complement of external 480-gallon fuel tanks and heavy bombs (symmetrically and asymmetrically loaded), and fully developed spins to 120 deg/sec. The test team used a phased approach, which systematically increased the team's knowledge of the airplane such that each increment in risk was led by an increase in the team's confidence in the airplane and supporting models.

Phase 1 testing examined the departure susceptibility by the application of single axis inputs at various flight conditions. Phase 1 also provided the updates to the simulation aerodynamic model that proved crucial to the safe execution of later phases.

Phase 2 provided the first look at upright and inverted spins, and sustained out of control flight modes. Spins deliberately preceded aggressive maneuvering (Phase 3) so that any unpredicted departures would be expected to place the test team back into familiar terrain.

Phase 3 opened the envelope for aggressive maneuvering, and included the full spectrum of multi-axis aggravated maneuvers, spins to high yaw rates (120 deg/sec), and zero-air-speed tail-slides.

Initially these phases were strictly followed with no wing stores on a specially equipped single-place (E-model) airplane.<sup>†</sup> The sequence was then repeated in each of the desired symmetric external store loadings, followed by limited scope tests of the two-place (F-model) airplane.

Finally, asymmetric stores testing was completed in phases 4 and 5. Phase 4 consisted of single and multi-axis aggravated inputs and upright spins and inverted spins for asymmetric loadings up to 14,000 ft-lbs. Phase 5 consisted only of single axis inputs across a limited angle of attack range ( $\leq 25^\circ$ ) for weight asymmetries up to 28,000 ft-lbs. Over the course of three years, a total of 221 flights, and 378 flight hours were devoted to high-angle-of-attack maneuvering, departure resistance, and spin testing.<sup>6</sup>

<sup>†</sup> Modifications included a spin recovery parachute and emergency power accommodations.

## Dynamically-Scaled Model Testing

The three non-captive dynamic model test techniques (spin, free flight, and drop model as shown in figure 2), have been instrumental in understanding some of the complex types of behavior of fighter aircraft at extreme angles of attack. They are subsonic techniques and, in combination, cover a wide range of high-angle-of-attack behavior as shown in figure 3. These techniques complement each other to improve the overall understanding of the spin and recovery characteristics. For example, drop model tests are used to augment the results obtained by spin tunnel testing. In this regime, drop model test points, which are typically limited in number, serve to spot check the more statistically significant spin tunnel results. Additionally, the influence of model scale (affecting issues from manufacturing tolerances to Reynolds number effects) is potentially exposed owing to the diverse scale factors between the 3.6%-scale spin-tunnel model and the 22%-scale drop model.

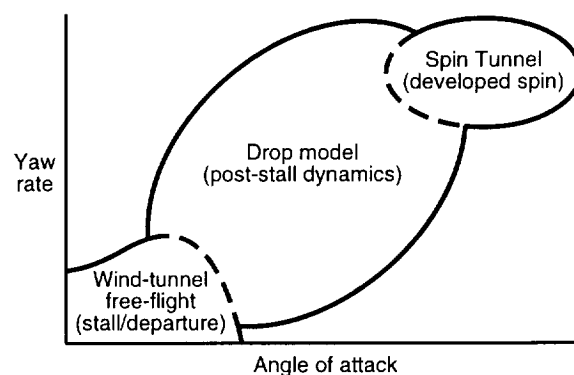


Figure 3.- Dynamic model test techniques.

The scale models used in all of the non-captive tests must be dynamically scaled to accurately represent the full-scale aircraft flight dynamics. This not only requires geometric scaling, but also requires maintaining the equality of the scale model and full-scale airplane ratios of inertial effects to gravitational effects.<sup>7,8</sup> Therefore, the units of length are scaled from geometric ratios; units of mass are scaled based on equal relative density factors; and time is scaled based on equal Froude numbers. Table I provides the factors needed to determine the dynamically scaled model properties. The scaling factors must be properly applied throughout all areas affecting the flight dynamics. For example, time scaling sets the requirements for actuator response time, flight control

computer frame rate, filter performance, and *any* other time related quantity<sup>‡</sup>.

Table I.- Scale Factors for Dynamic Models.

Model values are obtained by multiplying airplane values by the following scale factors where  $N$  is the model-to-airplane scale ratio,  $\sigma$ , is the ratio of air density at the airplane altitude to that at the model altitude,  $\ell$  is a representative unit of length,  $m$  is the vehicle mass, and  $g$  is the acceleration due to gravity.

Quantity	Scale Factor
Linear dimension	$N$
Relative density ( $m/\rho\ell^3$ )	1
Froude number ( $V^2/\ell g$ )	1
Weight	$N^3/\sigma$
Moment of inertia	$N^5/\sigma$
Linear velocity	$N^{0.5}$
Linear acceleration	1
Angular velocity	$N^{-0.5}$
Time	$N^{0.5}$

#### Drop Model Test Technique Description

Figure 3 shows that a significant void of information exists between the pre-stall and stall departure results produced by the free-flight tests and the fully developed spin behavior observed in the spin tunnel tests. The radio-controlled drop model technique was originally developed in the 1950's to fill this void, providing information on the post-stall and spin-entry motions of airplanes.

With the need to provide combat aircraft with the capacity to aggressively maneuver at and beyond stall, the drop model technique has been further developed to permit the investigation of the related flight dynamics issues while the test configuration is undergoing large amplitude, high rate maneuvers over the entire low-speed flight regime and is not solely focused on spin entry. For example, past drop model programs of other aircraft configurations have explored a variety of low-speed phenomena including highly dynamic motions such as divergent wing-rock, aggressive tumbling, and roll departures as well as more docile areas such as pitch control enhancement,

<sup>‡</sup> This is not a recent discovery nor is it inconsequential. Achieving scale time often has been the most demanding factor in subsystem selections; for instance, *every* upgrade to the drop model flight control computer hardware since the 1970's has been driven by scaled throughput requirements.

parameter identification, and control law refinements for accelerated and unaccelerated stability improvements.<sup>9,10,11</sup> As mentioned above, the high-angle-of-attack flight regime was not an afterthought for the F/A-18E/F program; indeed, all three of the dynamic model methods were conducted for this airplane including drop model.

The overall operation of the drop-model technique involves dropping an unpowered, dynamically-scaled model from a helicopter, flying it through a series of maneuvers by remote control from the ground, and recovering it with a flight termination parachute.

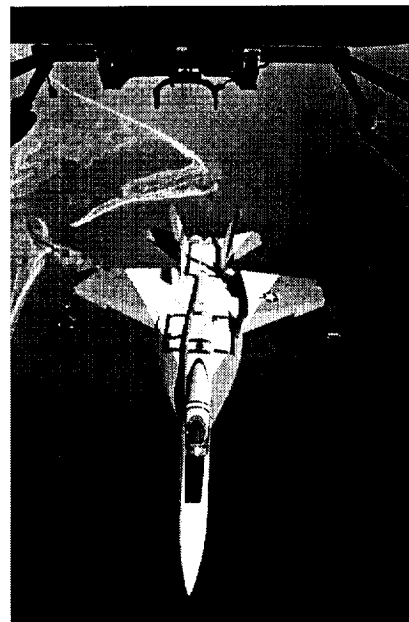


Figure 4.- 22% F/A-18E drop model.

Weighing from 880 to 1100 pounds (depending on the airplane store/fuel loading condition of interest), the 22%-scale F/A-18E/F model (pictured in figure 4) is dropped from altitudes of up to 15,000 feet (model scale) and is tracked by a manually operated ground-based tracker on which video cameras, a radar ranging system, and telemetry antennas are mounted.<sup>§</sup> In addition, a camera is mounted in the canopy of the model to provide an onboard-pilot's view.

<sup>§</sup> The equivalent airplane altitude depends on the model scale factor, the model-to-airplane mass ratio, and the air density: 15,000-ft model is about 35,000-ft full-scale equivalent.

The pilot sits at a control station and monitors data displays and the video images while providing three-axis control through a customized cockpit as shown in figure 5. The overall control loop consists of downlinked flight data, a digital computer on which the control laws are implemented, and a command uplink. Once the pilot has executed the intended profile, the onboard flight termination parachute is deployed to decelerate the model prior to splashing down into the ocean.



Figure 5.- Drop model cockpit.

The drop model carries an extensive complement of flight instrumentation to provide real-time state feedback information to the flight control computer, to drive real-time data displays for the ground-based pilot, and for post-flight data analysis. Duplex flight sensors measure angle of attack, sideslip, airspeed, 3-axis angular rates and linear accelerations, and 3-axis attitude. Simplex flight instruments include pitot and static pressures, radar range, pilot's-eye-view video, and control surface position transducers. Various system-monitoring parameters and all of the flight sensor signals are downlinked to a ground-based data logging system and, along with pilot comments, video imagery from the ground, and digital recordings of ground-generated signals (such as pilot commands and mode selections) form the collection of data obtained during a flight.

## **OVERVIEW OF AIRPLANE FLIGHT TEST RESULTS**

For the reader's benefit, a brief overview of the airplane falling leaf and spin recovery flight test results are presented here. More comprehensive discussions of the airplane flight test program and its results can be found in the references.<sup>5,6</sup>

### **Falling Leaf Out of Control Flight Mode**

The elimination of the falling leaf mode from the Super Hornet is just one of the design team's great triumphs. Although the mode naturally exists in the bare, unaugmented airframe, the E/F flight control laws successfully inhibit any undesirable motion. Despite extensive development flight testing and early operational evaluation, no sustained falling leaf has been observed in any loading, or at any permissible center of gravity location unless operating with the feedbacks disabled (CAS-off).

### **Spin Recovery**

The scope of the spin program included upright and inverted spins to 120 deg/sec, clean, symmetric and asymmetric external store loadings, FCS failure states, the full center of gravity range, misapplied recovery controls, and both E- and F-models.

As with the falling leaf testing, spins were initiated with the feedbacks disabled (CAS-off). Upright and inverted modes were identified. While the upright modes were more stable and repeatable, inadvertent entries from CAS-on departures favored inverted modes.

As predicted, recoveries in Auto Spin Recovery Mode were generally prompt with the application of full lateral stick with the yaw rate for upright spins, and against the yaw rate for inverted. Releasing the controls completed the recovery as the airplane restored CAS-on operation with the yaw rate unwinding through 15 deg/sec.

## **RESULTS**

The results from the drop model test program are grouped by phenomena: longitudinal control characteristics; spins (including several subtopics); an unusual attitude high rotation rate mode dubbed "cartwheel"; and a synchronized rolling and yawing motion often referred to as a falling leaf. Results from the other scale model and the aircraft tests are discussed along with these results where appropriate.

Airplane and drop model test results are often best conveyed on the printed page in the form of time-history plots of various flight parameters. Many of the quantities measured during drop model tests (including time itself) need to be scaled using the proper factors as discussed above. *All model*

quantities presented in this paper have been scaled to represent full-scale equivalent values unless explicitly indicated otherwise. Note that the lateral-directional pilot inputs (lateral stick and pedal) are normalized such that full throw equates to  $\pm 1$  unit which is not the usual convention for the airplane but allows for co-plotting.

### Longitudinal Response

The F/A-18E/F must possess significant levels of pitch control throughout its large trim angle-of-attack range to meet the high demands placed on it as an air superiority fighter.<sup>12</sup> One particular area of interest is its ability to generate nose-down recoveries from anywhere within this range and to do so with sufficient authority to overcome opposing moments generated by inertia coupling or other effects. Several of the aforementioned test methods provide information relevant to this topic including static tests, free-flight tests, and drop model tests. Meeting pitch control margin requirements is a complex endeavor due to factors that must be addressed such as thrust effects and entry conditions and is beyond the scope of this study. However, the basic longitudinal response characteristics can be assessed with the drop model.

Results from static low-speed aerodynamic tests of a 15%-scale model of the F/A-18E configuration in the 30- by 60-Foot Wind Tunnel illustrate some of the fundamental longitudinal characteristics of the configuration. Untrimmed lift and pitching moment coefficient data are shown in figure 6 for symmetric horizontal tail deflections across the entire deflection range of  $-24^\circ$  to  $+20^\circ$  with fixed LEF/TEF deflections of  $34^\circ/4^\circ$  for an aft center of gravity location of 29.4% mean aerodynamic cord. As mentioned above, these data indicate that the configuration can be trimmed across a large angle-of-attack range that encompasses the angle of attack for maximum lift. Also, the angle of attack for minimum nose-down control power occurs near the same point. These static test results were used to direct studies of similar phenomena using free-flight and drop model tests.

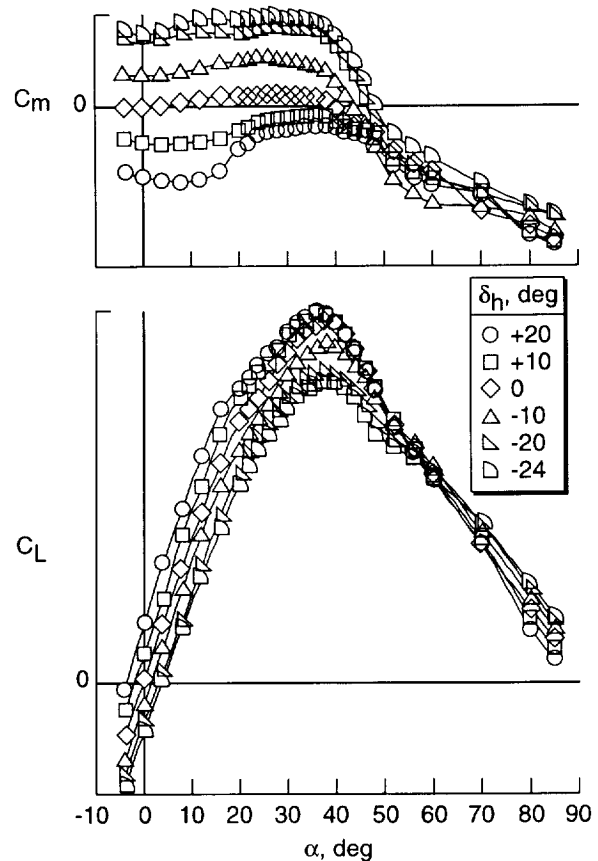


Figure 6.- Effect of horizontal tail deflection on static longitudinal characteristics.

Maneuvers were performed during the free-flight and drop model tests where the respective models were stabilized near maximum lift and a forward pitch stick input was rapidly applied. The responses through maximum pitch acceleration and pitch rate were measured and indicated that good levels of pitch authority exist.

Similar maneuvers were performed with the airplane as shown in figure 7 where airplane and drop model time-histories are co-plotted. These data show that the drop model results correlate well with those from the airplane.

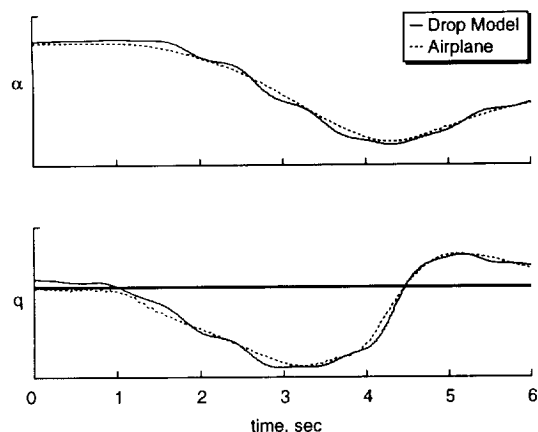


Figure 7.- Longitudinal response characteristics for drop model and airplane.

### Spins

Extensive studies of the spin characteristics of the F/A-18E/F involved spin tunnel, full-scale aircraft, and drop model testing - each of which has contributed uniquely and corroboratively to the overall spin investigation. The free-spin tests conducted in the Langley 20-Foot Vertical Spin Tunnel with a 1/28<sup>th</sup>-scale model identified upright and inverted spin modes for the F/A-18E/F.<sup>13</sup> Those tests encompassed a wide variety of mass properties (both symmetric and asymmetric) that spanned the operational envelope for both the E- and F-models. During each particular spin test point, the control surfaces either remain fixed or were moved from one preset position to one other preset condition (i.e., these were open-loop tests with no state feedbacks). For the symmetrically loaded configuration the highest rate upright spin was a fast (spin rate = 200 deg/sec), flat ( $\alpha$  from 78° to 90°) mode occurring with fixed pro-spin controls. This rate exceeded the spin rotation limit placed on the airplane during the flight-testing phase. As such, certain aspects of follow-on spin testing would be relegated to the drop model as discussed below.

Spin recovery properties were also determined in the spin tunnel tests for a similarly wide range of conditions and indicated that the configuration has satisfactory recovery characteristics using aerodynamic controls. For example, recovery from the aforementioned spin mode was 3<sup>3</sup>/<sub>4</sub> turns using ailerons into and rudder against the rotation direction. Spin tunnel tests also identified the salient features of the emergency spin recovery parachute system implemented on the full-scale high-angle-of-attack

test aircraft. A complete account of the spin tunnel investigation is given in reference 13.

The remainder of this section relates to the drop model and full-scale spin tests. Except during the spin resistance tests, all upright and inverted limited-rate spin tests of the drop model and airplane were conducted using the manually activated spin mode to generate the large control surface deflections needed to drive the vehicles into spins. The control and mode sequencing was similar for the upright and inverted cases with the obvious differences. In both, the longitudinal stick was applied followed by spin mode selection, pedal deflection, and, after a delay, the lateral stick was ramped in while the longitudinal stick was relaxed. Upright spins were initiated from a full aft stick condition and were generated using cross controls (lateral stick direction opposite to the pedal direction); inverted spins started from forward stick and required coordinated controls. The recovery method for both the upright and inverted spins was to disengage the spin switch, neutralize pedal, and reverse the lateral stick (i.e., lateral stick into the direction of the spin arrow).

The discussions of the spin tests are organized into five subsections: the first two address the incipient spin properties whereas the final three include the developed spin and recovery aspects.

Spin resistance. The spin tunnel results indicated that the F/A-18E/F spin modes are fully recoverable using full-authority control deflections. Accordingly, the aircraft control system designers implemented a sophisticated spin mode logic that provides full authority command capability from the command stick and rudder pedals and serves as a pilot-directed spin recovery scheme (as opposed to a totally autonomous spin *prevention* scheme).<sup>14</sup> This mode is normally armed automatically so that inadvertent encroachments into the incipient spin regime can be positively and rapidly arrested by the pilot. Note that to engage anti-spin controls, the pilot must deflect the lateral stick in the anti-spin direction; otherwise, the control laws remain in CAS mode. However, the spin mode can be manually entered to perform intentional spin maneuvers (discussed later). The CAS mode provides departure/spin resistance by, among other means, reducing excessive control deflections at high angles of attack. The effectiveness of the scheme is demonstrated by the drop model data of figure 8 where the pilot applied and sustained full

pro-spin (cross) controls while remaining in CAS mode from a full aft stick initial condition. The yaw

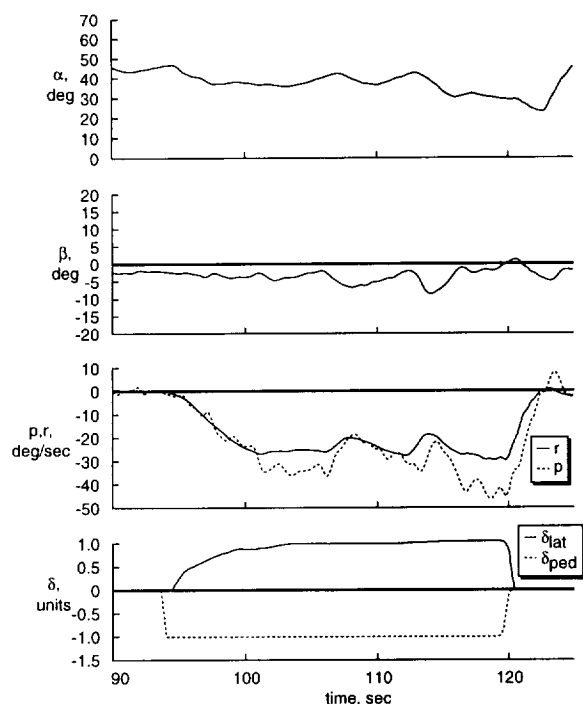


Figure 8.- Spin resistance in CAS mode for drop model.

rate smoothly accelerated reaching a very manageable maximum of about 30 deg/sec with only slight oscillations in sideslip: the model showed no propensity to depart. In fact, the maneuver is a moderate-angle-of-attack coordinated roll that was very quickly terminated when the pilot neutralized controls. Thus, the CAS mode provides high levels of departure/spin resistance while maintaining a good degree of maneuverability even in the presence of pro-departure pilot inputs. In the next sections, the manually activated spin mode was used to generate greater amplitude control deflections so that the developed spin properties could be investigated.

Sustaining the spin. Throughout the course of spin testing, both the drop model and the airplane had difficulty sustaining a spinning condition following what appeared to be reasonable spin entry maneuvers. The typical progression is shown in figure 9 where both drop model and airplane data are given.

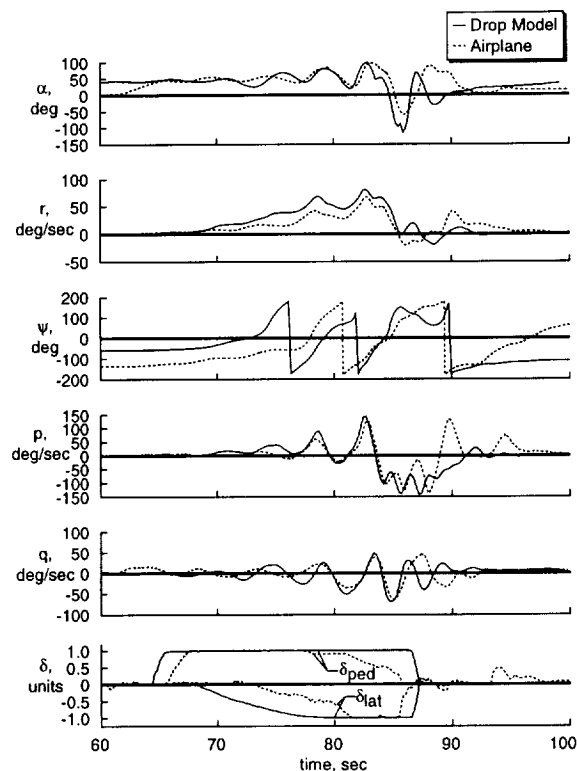


Figure 9.- Self-recovering spin from spin mode for drop model and airplane.

After application of pro-spin controls, the motion progressively became oscillatory (notably in angle of attack, roll rate, and pitch rate) as the yaw rate developed. The lateral oscillations grew until the excursions reached sufficient amplitude, usually in the direction of the lateral stick (i.e., left roll in a nose-right spin attempt), to cause the angle of attack to kinematically decrease. Once at low angle of attack with large rolling surface deflections, the motions became roll dominated negating the yawing motion and producing a self-recovery from the spin. Note, too, that this considerably complex and dynamic condition is well represented by the drop model.

The difficulty to routinely achieve a sustained spin was most prevalent early in the testing sequences and became less so as more experience was gained. For the airplane, the use of split throttles augmented the aerodynamic yaw acceleration that, of course, was not available to the unpowered drop model. Instead, the drop model relied on sustaining a highly stabilized initial condition through the use of pilot selectable pitch and roll dampers. Once these methodologies

were developed, spins in the manually activated spin mode were routinely achievable.

Simulation-based spin predictions. A very extensive mathematical aerodynamic simulation of the F/A-18E/F containing approximately one million data points has been assembled using information from numerous static and dynamic wind-tunnel tests and analytical methods.<sup>15</sup> Nonetheless, the ability to accurately measure and, more importantly, to construct with confidence the proper math model formulations capable of representing even the fundamental dynamics (much less the subtle ones) in the highly complex non-linear high-angle-of-attack regime is often beyond the capacity of some of the current modeling methods.<sup>16</sup> Due to these uncertainties, it is prudent to perform a flight-to-simulation validation effort if possible.

Drop model flight data was used to assess the simulation math model in the spin regime. Five optional math model constructs of the rotational characteristics are included as a part of the simulation since research to determine the most accurate way to model rotational characteristics is ongoing. Simulation-generated data for the five options were compared to the drop model spin data. Of the five, the option that best matched the flight data is shown in figure 10 as "Simulation Option A." The overall spin rate and average angle of attack agrees well with the drop model data. However, the simulation produced smoother motions than the flight data indicate. The requisite pitch and roll oscillations needed to transform an emerging spin into a roll-dominated self-recovering motion are generally not predicted by any of the options. However, adding simple degradations in the linear pitch damping ( $C_{m_q}$ ) and roll damping ( $C_{l_p}$ ) terms improved the match as indicated by the "Simulation Option A + Mods" trace. These comparisons illustrate the process where flight data (from drop model or aircraft) can be used to validate or refine an aerodynamic database in terms of either selecting modeling approaches or creating incremental modifications.

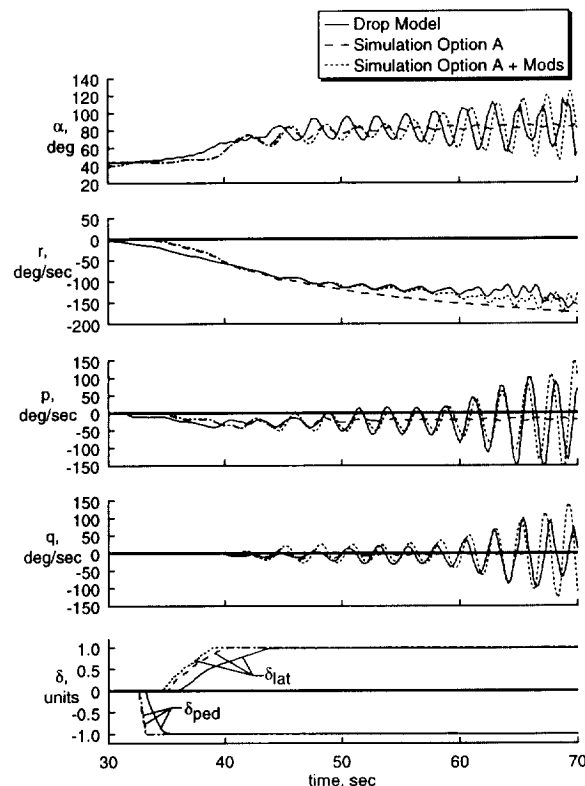


Figure 10.- Comparison of simulation modifications to drop model spin.

Limited-rate spins. The drop model technique is uniquely suited among the scaled model methods to perform spin *entry* maneuvers (recall that research in the Spin Tunnel begins with the developed spin). Accordingly, the drop model can be used to investigate spin maneuvers that fall short of reaching steady-state conditions. Since the airplane was limited to yaw rates below most of the predicted steady-state spin rates, the drop model is also the model method of choice to conduct airplane-to-scale-model correlations.

Limited-rate upright spin maneuvers from the airplane and the drop model, one of which is shown in figure 11, indicate that the vehicle is well behaved in the spin regime. Yaw rate increases smoothly in response to the command. Once at full lateral stick, the motions become oscillatory, but the yaw rate continues to increase. After about 2 turns the call to recover was made at a peak yaw rate of about 100 deg/sec. A rapid recovery was achieved in less than one turn.

Note that the airplane and drop model are in excellent agreement. The yaw rate buildup, the peak rate achieved, the recovery properties, and even the unsteady nature including the frequency of oscillation and to a high degree the amplitude of oscillation in angle of attack, yaw rate, and sideslip are all well represented by the drop model.

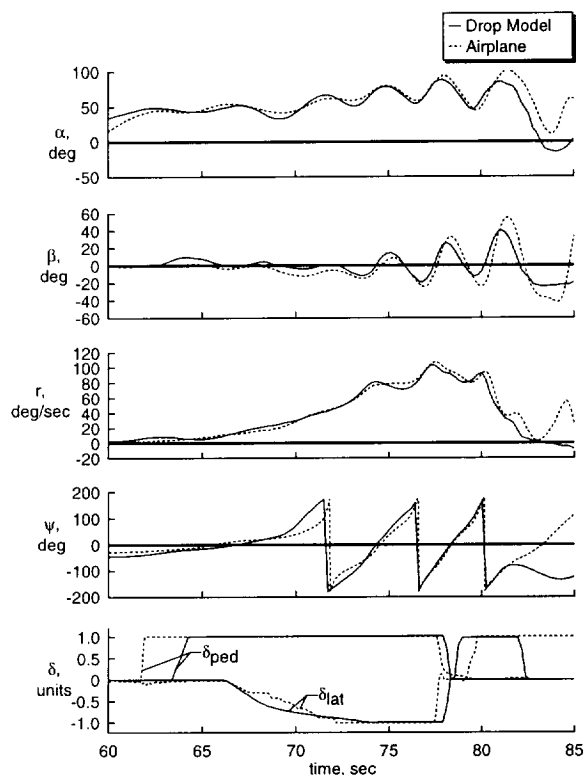


Figure 11.- Upright limited-rate spin for drop model and airplane.

The limited-rate inverted spin is similarly well behaved as shown in figure 12. Note that the aircraft time history has been spilt so that the entry commands and the recovery commands are synchronized between the drop model and airplane data (the spin condition was held for a longer period during the drop model maneuver). As in the upright case, once full pro-spin controls were applied and yaw rate had developed, the angle of attack coupled and the motions became more oscillatory. The yaw rate was allowed to reach a peak of about 90 deg/sec when recovery controls were applied. The spin was quickly arrested in approximately one turn.

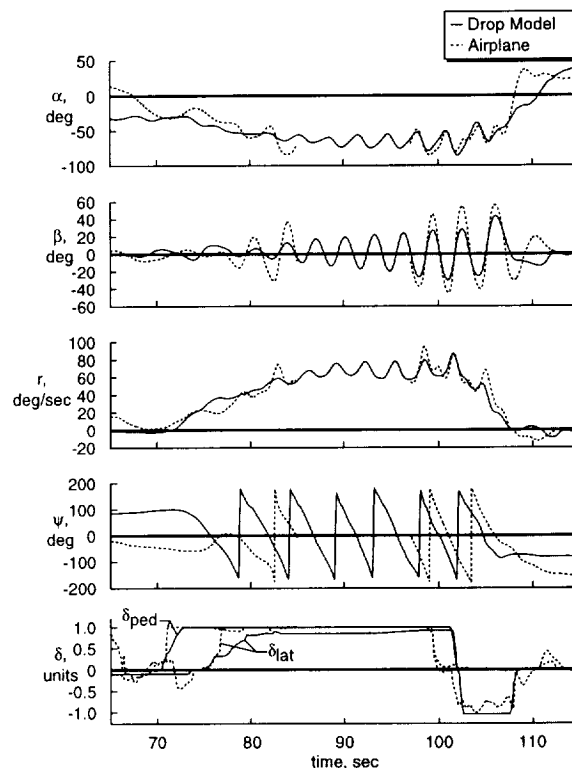


Figure 12.- Inverted limited-rate spin for drop model and airplane.

As in the upright case, the drop model inverted spin properties are in excellent correlation with the airplane. Additionally, since the pro-spin controls were held for a longer time, the drop model results indicate that the spin remains benign while the pilot sustains pro-spin inputs for approximately 5 turns (verses 2 turns as obtained during the airplane test).

The very high level of agreement between the drop model and the airplane validates the drop model technique. With its viability established, the drop model can be used with confidence to off-load or augment the airplane's flight testing efforts. To a limited extent, both of these aspects were accomplished during the F/A-18E/F drop model program and are discussed next.

Beyond basic limited-rate spins. For varying reasons, certain maneuvers were not performed during the full-scale flight test program. For instance, since the spin characteristics for the E- and F-models were expected to have certain similarities, it was prudent to avoid unnecessary safety risks incurred by extensively testing an unmodified F-model aircraft (recall an E-model was equipped with special flight test

emergency recovery systems). As such, spin test points for the F-model were limited to upright attitudes to avoid prolonged exposure to extreme negative angles of attack conditions where the engines are more susceptible to stall. However, to further increase confidence that F-model spin recovery characteristics are similar to the E-model, the drop model was used to explore the inverted spin.

The drop model data of figure 13 confirm strong similarities exist in the inverted spin characteristics between the E- and F-models. Note that the F-model maneuver is split in order to synchronize the entry and recovery portions of the maneuver. Very similar yaw accelerations, peak rates, and yaw decelerations are evident. In both cases, positive recovery was quickly realized within one turn after application of recovery controls.

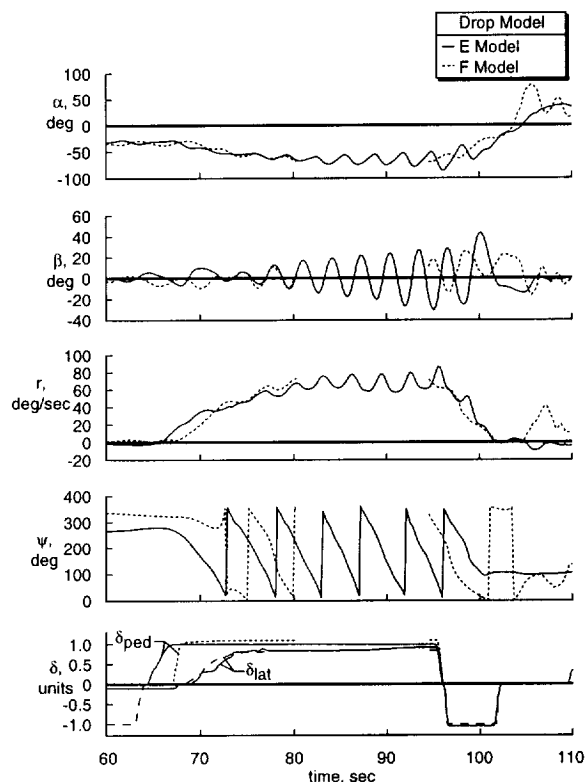


Figure 13.- Inverted limited-rate spin for E and F drop model.

The drop model was also used to augment the full-scale vehicle testing by exploring conditions beyond the limits imposed on the airplane, both in terms of lateral weight asymmetry and rotation rate.

As mentioned above, the phase 4 airplane flight testing included spins with lateral weight

asymmetries up to 14,000 ft-lbs. and phase 5 expanded the asymmetry to 28,000 ft-lbs. but restricted the angle of attack; hence, no spins were conducted with this loading. Drop model tests were used to examine the spin conditions at the 28,000 ft-lbs. asymmetric loading out to a spin rate of 90 deg/sec in the more severe direction of heavy wing out. Tests were performed for the E-model (upright spins) and the F-model (inverted spins). The data showed that with the asymmetric store loadings, both models were more prone to enter the spin, yet recoveries occurred within 3 turns. These results indicate that no unexpected accelerations were present for the extreme store loadings tested.

High rate spins tests were performed with the drop model to observe the nature of the spin as it evolves towards steady state beyond the imposed airplane flight-test spin rate limit of 120 deg/sec. During these tests an unusual and extreme rotation mode (cartwheel) was uncovered and is the topic of the next section. However, note that while the motion is extreme, it does not occur suddenly, and recoveries were always achieved. As such, the interest is more academic since a pilot would have ample opportunity to affect recovery well before the cartwheel onset.

### Cartwheel

High rate spin tests with the drop model were performed in the same basic manner as the limited-rate spin studies where the spin mode was engaged manually to allow for large control surface deflections. The data of figure 14 show the effect of sustaining pro-spin controls for approximately 45 seconds. As with the limited-rate spins, the yaw rate smoothly increased as the pilot applied pro-spin lateral stick. At full lateral stick, the motions became somewhat oscillatory, yet yaw rate continued to increase and began to level out at 115 deg/sec. Sustaining the pro-spin controls for an additional three turns resulted in an increase in yaw rate and the onset of the cartwheel motion. As the cartwheel motion evolved, the yaw rate began to level off near 180 deg/sec, but the maneuver was terminated prior to reaching an equilibrium condition.

The cartwheel is an inclined spinning motion characterized by the rotation vector becoming normal (or nearly so) to the velocity vector. The angle between these vectors, given by  $A_{V\Omega}$ , increased to a

maximum average value of about  $60^\circ$  during the cartwheel maneuver as shown in figure 14.

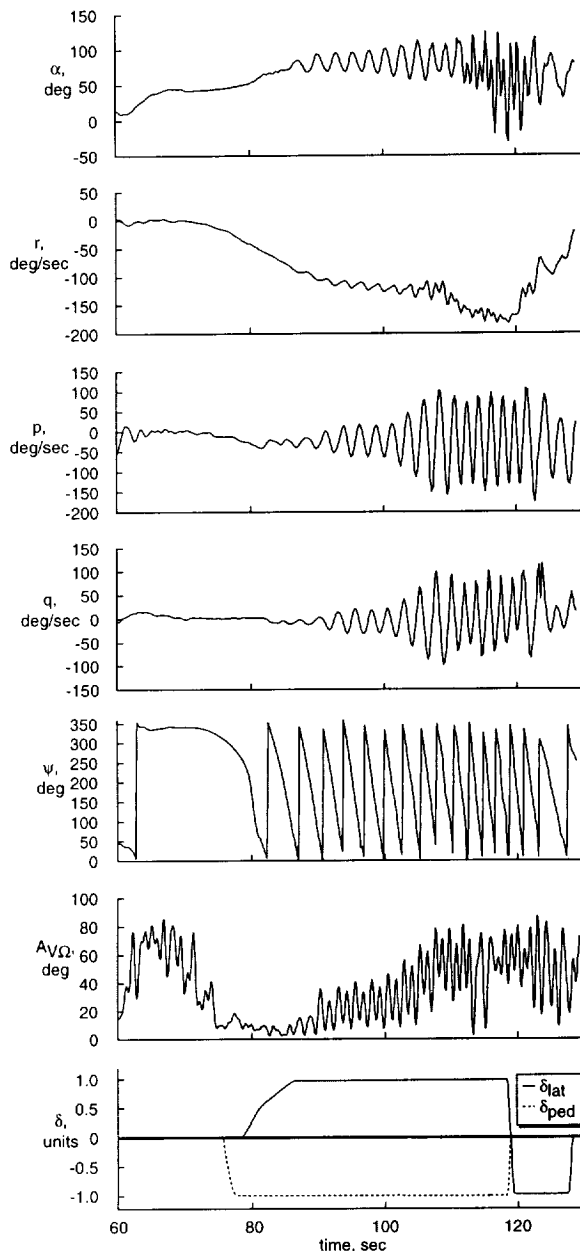


Figure 14.- Drop model cartwheel.

Rigorously, a pure cartwheel motion occurs when the vectors are truly orthogonal ( $A_{V\Omega} = 90^\circ$ )<sup>\*\*</sup>, and the

<sup>\*\*</sup> Note that large values of  $A_{V\Omega}$ , may merely indicate the presence of a pitching motion as is evident at the beginning of the time history. A pure pitch motion also produces an  $A_{V\Omega}$  of  $90^\circ$ .

motion is dominated by body-axis yaw rate. Then, the angle of attack time history would be a series of steps<sup>††</sup> alternating between  $0$  and  $180^\circ$  while sideslip would sinusoidally vary with an amplitude of  $\pm 90^\circ$ . Superimposed on this motion is a slow precession of the rotation vector, observed in this test to have a period on the order of 20 seconds. Regarding the pilot's g-environment, the cartwheel produces loadings similar to any high-rate spin: inclining the spin axis realigns the Earth's 1-g field with respect to the pilot, but the rotational contributions dominate as is the case of a fast un-inclined spin.

As mentioned before, even though the motion is extreme, it does not come on abruptly: several unmistakable spin turns precede the yaw acceleration associated with the cartwheel affording ample opportunity to recover. Furthermore, the  $180$  deg/sec rotation was arrested within 3.5 turns using standard recovery controls (neutral pedal and lateral stick in the direction of the yaw rate).

This unusual cartwheel motion was also observed during the free-spin tests in the Spin Tunnel and during simulation studies. However, for different reasons, the results from these techniques were difficult to trust without further corroboration from the drop model. In the Spin Tunnel, the motion was difficult to observe for very long since the radius of the precession path quickly grew larger than the tunnel test section. Furthermore, launch dynamics could not be completely ruled out: since the model is hand-launched with pre-rotation, it is possible to inadvertently incline the spin axis to the velocity vector. In the simulation, the rates and motion amplitudes were so large that the validity of the aerodynamic math model was suspect. This was particularly so in light of the math model's inability to represent the oscillatory nature of the normal spin as previously discussed. However, with the aforementioned degradations to the linear pitch and roll damping terms in place, the simulation is in good agreement with the drop model flight data as shown in figure 15. The simulation represents the overall levels of yaw rate and even the oscillations in the motion. For the simulation run, the controls were sustained until a steady-state condition was reached. The simulation prediction indicates a peak yaw rate of about  $280$  deg/sec develops before the motion stabilizes at nearly  $200$  deg/sec. Once at the

<sup>††</sup> Sensor dynamics, signal conditioning, and the like may alter the *measured* angle of attack waveform.

steady condition, the angle-of-attack waveform is indicative of a nearly pure cartwheel motion.

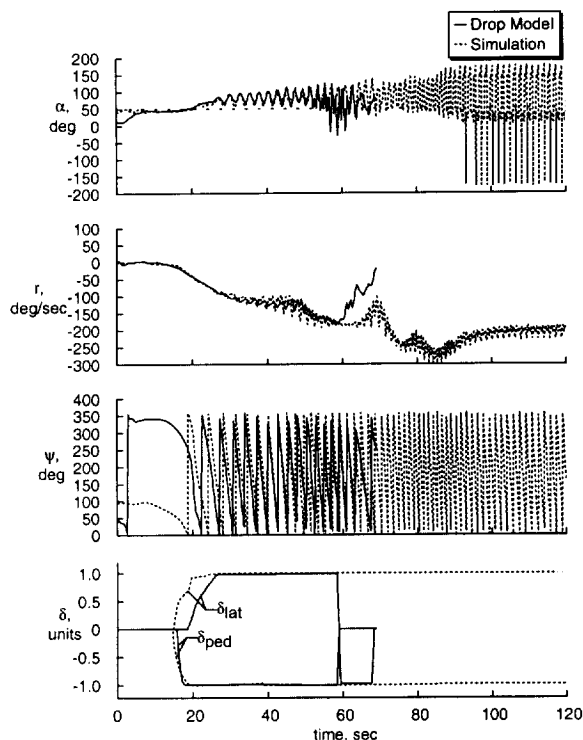


Figure 15.- Cartwheel for drop model and simulation.

The simulation was used to continue to study the cartwheel phenomenon. Like a spinning top, the motion is dependent on complex rigid-body dynamics that include precession and nutation effects, and the motion was found to be highly dependent on the inertia and mass properties. Preliminary results from the simulation indicate the cartwheel phenomenon is prevalent only over a relatively small range of mass characteristics.

The cartwheel mode, though of little real consequence operationally to the F/A-18E/F, may have general implications more applicable to other configurations or even other classes of vehicles. As such, research in this area needs to continue. This highly dynamic motion requires the use of a variety of ground-based tools in order to gain confidence in the analysis methods and the concomitant findings. The drop model can provide the flight data that the other techniques can use to validate against.

## Falling Leaf

Another large amplitude dynamic motion, one that is relevant to the F/A-18, is an out of control motion known as the falling leaf mode. This mode can pose a significant safety-of-flight hazard. It is characterized by in-phase rolling and yawing motions and can, in severe cases where the resulting nose-up inertia coupling is high, prohibit recovery to low-angle-of-attack flight. Research<sup>17</sup> into this phenomenon has produced a predictive measure, the synchronous roll yaw parameter (SRYP), that only requires static and dynamic stability derivatives and the vehicle inertias; an evaluation of SRYP indicates the un-augmented F/A-18E/F is susceptible to the falling leaf mode. Note that SRYP is the value of the predicted ratio of the peak yaw rate to peak roll rate and will be discussed below. As mentioned above, the control law design team successfully eliminated the falling leaf mode from the augmented airplane.

During the airplane flight tests, falling leaf maneuvers were achieved, but only while using the spin mode to manually override the CAS. Even at that, the maneuvers were fairly difficult to establish and, like the spin, required a certain piloting technique. The results from those maneuvers can be used to validate the falling leaf analysis method's peak rate ratio predictions for the flight conditions obtained. To evaluate the prediction tool beyond those conditions, it is desirable to use a flight vehicle, like the drop model, to collect data at extreme mass conditions. First, however, the suitability of using an unmanned vehicle to conduct falling leaf research needed to be determined.

Tests were conducted with the F/A-18E/F drop model at a condition where lessons learned from the full-scale flight test could be employed. It was found that using a pilot-enacted computer-generated sinusoidal stick command that mimicked the piloting technique used during the full-scale tests produced the best results in the drop model tests. The maneuver, shown in figure 16, was initiated at a high-angle-of-attack wings-level condition.

An asymmetric two-cycle sinusoidal signal was superimposed on the lateral stick to excite the motion. Following the input wave train, the model underwent 3.5 cycles of the falling leaf motion. The ratio of the peak yaw rate to peak roll rate was 0.35; this is in excellent agreement with the airplane test result of 0.34 for the condition tested. The falling

leaf motion was quickly damped when the CAS mode was re-engaged - a finding consistently noted during the full-scale flight tests.

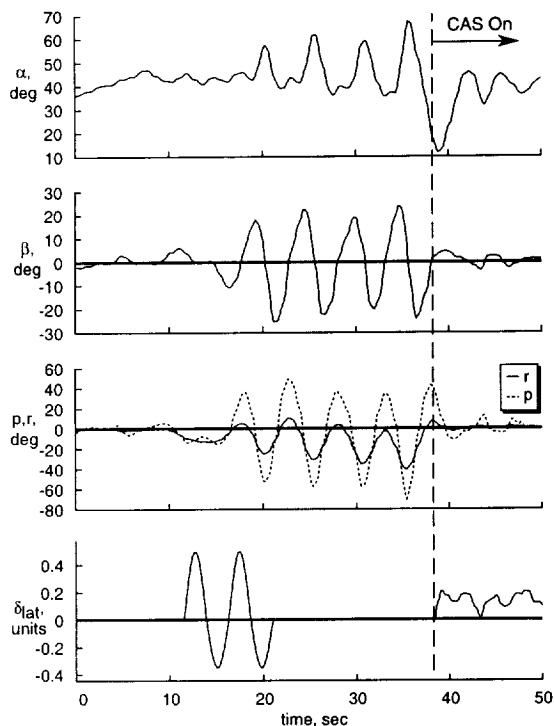


Figure 16.- Falling leaf for drop model.

For this test condition, several findings are apparent: the theory and the drop model validate against the airplane, and the drop model is capable of performing this type of research. Whether the model method can independently uncover this motion (without, for example, relying on a previously determined potentially vehicle-specific piloting technique) is still to be determined. However, the drop model is well suited for these studies since it inherently possesses the complex aerodynamics associated with this large amplitude phenomenon.

### CONCLUSIONS

Drop model tests were performed as part of a comprehensive investigation into the subsonic flight dynamics of the F/A-18E/F. The tests were conducted to provide information to the aircraft development program and follow-on full-scale flight tests in areas deemed beyond their scope (for safety or schedule reasons). In the course of pursuing this goal, drop model data were collected that illustrate the ability of a dynamically-scaled drop model to predict

the flight dynamic characteristics of the full-scale airplane. Furthermore, conducting drop model tests afforded an opportunity to expand knowledge in the field of low-speed high-angle-of-attack flight dynamics. The key findings from the drop model tests are summarized below.

1. The current results show that the drop model test technique can be used to accurately predict high-angle-of-attack flight dynamic characteristics. The F/A-18E/F drop model data exhibited excellent correlation with full-scale airplane results, even during highly dynamic maneuvers including spins and falling leaf maneuvers where complex flowfields dominate the aerodynamics.
2. Test data collected by the drop model predict excellent departure resistance and spin recovery characteristics during maneuvers beyond the scope of the full-scale flight test program. The areas investigated included upright and inverted departure / spin characteristics with and without extreme asymmetric weight loadings.
3. An unusual inclined spin mode, dubbed the "cartwheel", was discovered during the drop model testing while at extreme spin conditions. This characteristic is not considered to be an operational concern for the full-scale vehicle, since prolonged pro-spin inputs were required to expose this spin mode. However, the cartwheel is of interest from a flight mechanics standpoint and future aircraft programs may want to evaluate the possible existence of this unusual characteristic.

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